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THESIS

THE EFFECTS OF PARAMETER VARIATION
ON
HELICOPTER PERFORMANCE

by

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March 1985

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Although strong positive or negative effects may be observed at some velocities, indicating that trade-offs must be made in the design process in order

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The Effects of Parameter Variation on Helicopter Performance

by

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Major, Republic of Korea Air Force
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I. INTRODUCTION

A. PARAMETER VARIATION

The Conceptual Design process for a helicopter involves variations in the geometric parameters in an effort to obtain the best design. Some of the parameter changes are a result of performance considerations, for example, having a minimum amount of power required at the velocity desired for normal cruise flight, while some of the changes are a result of external requirements, such as having the aircraft fit in a transport plane.

The first steps in the Conceptual Design are based on the requirements of the system specification and historical trends. An example of trend information is that the Aspect Ratio (radius divided by chord) of the main rotor of a single-rotor helicopter usually lies between a value of fifteen and twenty [Ref. 1]. This means that if a first iteration rotor radius is selected, the designer already has an indication of the required chord of the rotor. Because of the different trend relationships, the actual range of parameter values available to the designer may be limited due to more than one reason.

B. POWER FUNCTIONS

The basic sizing parameters affecting the main rotor are the radius, the chord and the rotational velocity of the rotor. Due to the fact that these principal sizing parameters have non-linear effects on the total power required, it is necessary to consider the component power functions in an analysis [Ref. 2]. These power functions are as follows:

INDUCED POWER - That portion of the total power that is used to develop the thrust of the helicopter. This power is used to 'pump' air through the rotor in order to develop a lifting, or thrust, force to balance the weight of the vehicle.

PROFILE POWER - That portion of the total power that is used to overcome the drag of the rotating blades (blade torque).

PARASITE POWER - That portion of the total power that is used to overcome the drag of the fuselage. This is principally a function of the forward and/or vertical flight velocity, but some parasite power is required to overcome the effect of rotor downwash on the fuselage, even in hover. Inasmuch as this power is generally less than three percent (3%) of the total power, it will not be considered in this analysis.

C. INDUCED POWER

Induced power required at zero velocity (hover) can be represented most simply by use of Momentum Theory as shown in Equation (1-1)

$$Pi = [W^{3/2}/\sqrt{2\rho\pi R^2}]\cdot[1/B]/550 \text{ HP} \qquad (1\text{-}1)$$

where,

Pi = Induced power (horsepower)

W = Gross weight (pounds)

ρ = Atmospheric density (slugs/feet^3)

R = Rotor radius (feet)

B = Tip Loss Factor

From Equation (1-1) it may be seen that the Induced Power required is an inverse function of the rotor radius. This is logical inasmuch as with a very small radius, one would have to 'pump' much more air in order to generate the same amount of thrust.

Neither rotor blade chord nor rotational velocity appear in Equation (1-1). This is due to the fact that this Equation is based on Momentum Theory and it is assumed that a blade of sufficient size (chord) is turning at a sufficient rotational velocity to generate the required thrust. Rotational velocity (radians per second) is usually combined with the rotor radius (R) and expressed as

tip velocity in feet per second.

$$V_T = \Omega R \qquad (1\text{-}2)$$

The thrust for a rotor system may be expressed as,

$$T = \tfrac{1}{6} b\ c\ \rho\ (\Omega R)^2\ R\ \overline{C_L} \qquad (1\text{-}3)$$

where,

b = Number of rotor blades,

c = Chord (feet)

$\overline{C_L}$ = Average Coefficient of Lift.

As a helicopter moves from (hover) into forward flight, its transition through the air induces a flow velocity through the rotor that substitutes for a portion of the pumped velocity. This reduces the Induced Power requirements so that the faster the helicopter flies, the less Induced Power is required. This fact immediately gives the designer an idea of where the effects are the greatest. It has been shown in Equation (1-1) that the Induced Power is inversely proportional to the rotor radius. It can be seen, therefore, that changing the radius will have the greatest effect at hover, and the effect will diminish as the helicopter translates into forward flight.

D. PROFILE POWER

As has been stated, the Profile Power is that power required to overcome the drag of the turning rotor blades. At hover, this can be expressed as,

$$Po = \tfrac{1}{8}\ C_{do}\ \rho\ \sigma\ A\ V_T^{\,3} /\ 550\ HP \qquad (1\text{-}4)$$

where,

Cdo = Average profile drag of rotor blades

σ = Ratio of rotor blade area to rotor disc area (Solidity) $(bc/\pi R)$

A = Rotor disc area (πR^2) feet

From Equation (1-4) it may be seen that variations in rotor radius have a complex effect on the Profile Power dependent on whether just the rotor disc area is changed, the solidity is changed, the tip velocity is changed, or combinations of these factors.

In forward flight the profile power increases as the square of the ratio of the forward flight velocity (V_f) to the tip velocity (V_T), as shown in Equation (1-5),

$$Po = Po(1 + 4.3\mu^2) \qquad (1\text{-}5)$$

where,

$\mu = V_f/V_T = V_f/\Omega R$

From Equation (1-5) it may be seen that a simple change of the rotor radius (with all other factors held constant) has the tendency to increase the Profile Power requirement, an opposite effect to what was seen with the Induced Power.

E. PARASITE POWER

The Parasite Power function is that portion of the total power that is used to overcome the drag of the fuselage. Rather than expressing drag coefficients for the fuselage, it is usual to use an Equivalent Flat Plate Area

(EFPA), which is the area that would produce the same amount of drag with a drag coefficient of 1.0. The Profile Power of a helicopter in forward and/or vertical flight is shown as,

$$Pp = [\tfrac{1}{2}\rho f_f V_f^3 + \tfrac{1}{2}\rho F_v V_v^3]/550 \text{ HP} \qquad (1\text{-}6)$$

where,

f_f = EFPA in forward flight (feet^3)

f_v = EFPA in vertical flight (feet^3)

It may be seen from Equation (1-6) that none of the three primary rotor papameters, radius, chord and rotational velocity, are factors of the Parasite Power Requirements.

F. THE PROBLEM

Because the three principal parameters have non-linear effects, both singularly and in concert on the total power requirements, it is necessary for the designer to make many calculations during the Conceptual Design phase. Without some indication of the nature of the results of any changes, initial changes may be made in the wrong direction. For example, if the designer wishes to optimize the total power requirements at a velocity near the minimum power point, it is not readily apparent whether radius, for example, should be increased or decreased.

This project was undertaken, therefore, to develop some general trend information that could be used in the early

stages of a helicopter design, and, in particular, to make this information available to student in the course of instruction AE 4306 "Helicopter Design" at the Naval Postgraduate School.

II. APPROACH TO THE PROBLEM

A. CONSTANT PARAMETERS

In order to simplify the presentation of data, it was decided to vary only the basic geometric parameters of the main rotor system. As a result, it was assumed that an optimum airfoil section had been selected, and this section had a fixed value of profile drag coefficient (Cdo), a uniform twist (θ_T) and that the rotor blade was rectangular with respect to an equivalent chord.

In addition, all calculations were made at standard sea level conditions.

B. VARIABLE PARAMETERS

The three basic geometric parameters of the main rotor system that were chosen to be variables were,

1. Rotor radius (R), feet
2. Rotor chord (c), feet
3. Rotor rotational speed (Ω), radians per second

Although but three parameters were varied, it was necessary to examine not only a change in a single parameter, but also changes caused by combinations of the three geometric values. As a result, six cases were developed. Three of these cases were primarily for radius variations, one was for a chord only change, and two cases were developed primarily for rotational velocity changes.

Because of both the equations used in determining component powers and the general considerations of helicopter performance, factors that include combinations of the three variables must also be considered. These include disc solidity (σ), rotor tip velocity (V_T), and disc area (A).

C. SOLIDITY

Solidity is the ratio of rotor blade area to rotor disc area,

$$\sigma = (b\ c\ R)/(\pi R^2) = (b\ c)/(\pi R) \qquad (2\text{-}1)$$

Solidity is used as a non-dimensional area ratio, for example in presenting the average lift coefficient of a rotor system by dividing the coefficient of thrust (a non-dimensional thrust measure) by solidity to give a non-dimensional lift (thrust per area) function.

To maintain a constant lift coefficient (a possible aerodynamic requirement) while developing a constant coefficient of thrust (a possible performance requirement), one must maintain a constant value of solidity. It can be seen from Equation (2-1) that if the radius is changed, the solidity can be maintained a constant only by simultaneous changing of the rotor chord. (of course the number of blades could also be changed, but only in integral multiples).

D. TIP VELOCITY

Because of the ease of measurement, the velocity of the tip of the rotor blade is generally used as a characteristic airfoil velocity parameter. The tip velocity is the product of the rotational velocity in radians per second and the rotor radius in feet,

$$V_T = \Omega R \text{ feet per second} \qquad (2\text{-}2)$$

It may be seen from Equation (2-2) that a change in the rotor radius will produce a change in the tip velocity. However, it may well be that the designer does not desire the tip velocity to change. In order to optimize the rotor performance in regard to power requirements, it is desired to have as high a tip velocity as possible. However, when the velocity of the rotor tip reaches the transonic speed range, compressibility effects will occur that produce an increase in the required power. These compressibility effects are a function of the total air velocity seen at the rotor tip, and this total is equal to the tip velocity alone at hover and is equal to the sum of the tip velocity and the forward velocity during forward flight.

In order to delay compressibility effects, the tip velocity is generally chosen at a value below the transonic range at hover, and is usually in the neighborhood of seven hundred (700) feet of second. If it is desired to maintain a tip velocity near this value it is necessary to vary the rotational velocity as rotor radius is changed.

E. DISC AREA

The disc area is the area of the circle enscribed by the rotation of the unconed rotor system,

$$A = \pi R^2 \tag{2-3}$$

Although disc area appears in the equations for helicopter performance, it is used principally as a convenience. In the equation for induced power, Equation (1-1), disc area is used because that is the basis for the Momentum theory development. Use of the area factor assumes that the rotor will consist of a sufficient number of rotor blades, each with a proper airfoil section and sufficient chord to provide a reasonable blade loading. In the equation for profile power, Equation (1-4), the product of the disc area and the solidity is simply the total blade area,

$$\sigma \cdot A = [(b\ c)/(\pi\ R)] \cdot [\pi R^2] = b\ c\ R \tag{2-4}$$

It is seen, therefore, that the disc area will change as the rotor radius will change.

F. THE SIX CASES

As previously mentioned, the first three cases are based essentially on changes in the rotor radius.

1. <u>CASE I - Radius Changes</u>

a. Chord is a constant (solidity varies)

b. Tip velocity is a constant (rotational velocity changes)

c. Disc area changes

2. CASE II - Radius Changes

a. Chord varies (solidity is a constant)

b. Tip velocity is a constant (rotational velocity changes)

c. Disc area changes

3. CASE III - Radius Changes

a. Chord is a constant (solidity changes)

b. Tip velocity changes.

c. Disc area changes

The next case considered involves rotor chord changes only

4. CASE IV - Chord Changes

a. Solidity changes

b. Radius is a constant

c. Disc area is a constant

d. Rotational velocity is a constant

e. Tip velocity is a constant

The last two cases to be considered involve changes in the rotational velocity.

5. CASE V - Rotational Velocity Changes

a. Tip velocity changes

b. Chord is a constant

c. Radius is a constant

d. Solidity is a constant

e. Disc area is a constant

6. CASE VI - Rotational Velocity Changes

a. Rotational velocity changes ONLY in tip velocity.

b. Tip velocity is a constant

c. Chord is a constant

d. Disc Area is a constant

e. Solidity is a constant

G. AIRSPEED

The power required for a helicoipter varies with its forward velocity. Therefore, each of these six cases were examined at three representative velocities:

1. Zero knots (hover)

2. Sixty knots (approximating cruise velocity)

3. One hundred fifty knots (approximating maximum velocity.)

Each of the six cases were considered at each of the three velocities.

III. SOLUTION OF THE PROBLEM

A. THE BASELINE HELICOPTER

A typical light utility helicopter, the UH-1N model, was used for the baseline data. It is to be noted that a different category helicopter, that is to say a heavier or a lighter vehicle, might have produced different results in some of the cases. However, what was desired in this project was a general description of trends.

The dimensions of the baseline helicopter are shown in Table I.

TABLE I
BASELINE HELICOPTER

	MAIN ROTOR	TAIL ROTOR
Radius (ft)	24.0	4.3
Chord (ft)	1.95	0.95
Cdo	0.009	0.009
Number Blades	2	2
Rot. Vel. (rad/sec)	30.8	174.0
Tip Vel. (ft/sec)	739.2	748.2

GENERAL	
Front Flat Plate Area (sq ft)	25.0
Tail length (ft)	25.8
Max Velocity (kts)	132.0
Gross Weight (lbs)	10,480.0
Density Altitude	Sea level
Rotor Height (ft)	13.0
Skid Height (ft)	100.0

B. PERFORMANCE OF THE BASELINE HELICOPTER

Using the equations of Ref. 2, the power requirements for flying the baseline helicopter were determined at standard sea level conditions, out of ground effect (OGE) for three different

velocities. The total power required for the helicopter [PT(a/c)] consists of the sum of the main rotor power [PT(mr)] and tail rotor power [PT(tr)]. Each of these powers can be further divided into induced power [Pi] and profile power [Po], plus fuselage parasite power [Pp] as noted in Chapter I.

C. PARAMETER VARIATIONS - GENERAL

For each of the six cases discussed in Chapter II, a variation was made in one principal parameter in the amount of five and ten percent above and below the baseline value. The component and total powers were then computed for each of the four variations from the baseline value. Tables III-VIII, X-XV, and XVII-XXII are tabluations of the results of these variations. For each case, the Table shows:

1. The values of the principal variable
2. The other variables
3. The main rotor component and total powers and the total power required for the aircraft.

D. PARAMETER VARIATION - HOVER

The performance of the baseline helicopter was computed at zero forward velocity (hover) at standard sea level, as shown in Table II, and then variations were made for each individual case with the velocity remaining a constant at zero knots.

TABLE II
HOVER POWER REQUIREMENTS

	MAIN ROTOR	TAIL ROTOR	AIRCRAFT
Induced Power (HP)	698.0	55.7	
Profile Power (HP)	183.9	16.6	
Parasite Power (HP)	0.0		
Total Power (HP)	881.9	72.3	954.2

1. CASE I-0 [Rotor Radius I]

For this case the rotor radius was varied while the rotor chord and tip velocity were held constant. This implies that the solidity was changed (Equation 2-1) as was the rotational velocity (Equation 2-2). Table III shows the results of these variations.

TABLE III
CASE I-0

Variables	Radius	$0.90R_0$	$0.95R_0$	R_0	$1.05R_0$	$1.10R_0$
		21.6	22.8	24.0	25.2	26.4
	Rot. Vel.	34.2	32.4	30.8	29.3	28.0
Power Required	PT(a/c)	1014.7	982.1	954.2	930.2	909.7
	Pi(mr)	779.9	736.7	698.0	663.2	631.7
	Po(mr)	165.4	174.6	183.8	193.0	202.2
	PT(mr)	945.3	911.3	881.8	856.2	833.9

2. CASE II-0 [Rotor Radius II]

For this case the rotor radius was varied while the solidity and tip velocity were held constant. This implies that the chord was changed (Equation 2-1) as was the rotational velocity (Equation 2-2). Table IV shows the results of these variations.

TABLE IV
CASE II-0

Variables	Radius	$0.90R_0$	$0.95R_0$	R_0	$1.05R_0$	$1.10R_0$
		21.6	22.8	24.0	25.2	26.4
	Rot. Vel.	34.2	32.4	30.8	29.3	28.0
	Chord	1.76	1.86	1.95	2.06	2.16
Power Required	PT(a/c)	997.5	973.2	954.2	941.9	933.3
	Pi(mr)	779.9	736.7	698.0	663.2	631.7
	Po(mr)	149.6	166.4	183.8	203.6	223.5
	PT(mr)	929.5	903.1	881.8	866.8	855.2

3. CASE III-0 [Rotor Radius III]

For this case the rotor radius was varied while the rotor chord was held constant. This implies that the solidity was changed (Equation 2-1) as was the tip velocity (Equation 2-2) and the disc area. Table V shows the results of these variations.

TABLE V
CASE III-0

Variables	Radius	$0.90R_0$	$0.95R_0$	R_0	$1.05R_0$	$1.05R_0$
		21.6	22.8	24.0	25.2	26.4
	Tip Vel.	665.3	702.2	739.2	776.2	813.1
	Area	1465.7	1633.1	1809.6	1955.0	2189.6
Power Required	PT(a/c)	979.97	961.4	945.2	957.8	972.2
	Pi(mr)	784.79	738.7	698.0	661.8	629.2
	Po(mr)	120.64	149.7	183.8	223.4	269.1
	PT(mr)	905.33	888.4	881.8	885.2	898.3

4. CASE IV-0 [Rotor Chord]

For this case the rotor chord was varied while the rotor radius was held constant. This implies that only the solidity was changed (Equation 2-1). Table VI shows the results of these variations.

TABLE VI
CASE IV-0

Variable	Chord	$0.90c_0$	$0.95c_0$	c_0	$1.05c_0$	$1.10c_0$
		1.76	1.85	1.95	2.05	2.15
Power Required	PT(a/c)	934.0	944.1	954.2	964.2	974.8
	Pi(mr)	698.0	698.0	698.0	698.0	698.0
	Po(mr)	165.4	174.6	183.8	193.0	202.7
	PT(mr)	863.4	872.6	881.8	891.0	900.7

5. CASE V-0 [Rotational Velocity I]

For this case the rotational velocity was varied while the rotor radius and chord were held constant. This implies that the tip velocity (Equation 2-2) was not a constant. Table VII shows the results of these variations.

TABLE VII
CASE V-0

Variables	Rot. Vel.	$0.90\Omega_0$	$0.95\Omega_0$	Ω_0	$1.05\Omega_0$	$1.10\Omega_0$
		27.7	29.3	30.8	32.3	33.9
	Tip Vel.	665.3	702.2	739.2	776.2	813.1
Power Required	PT(a/c)	912.8	931.8	954.2	980.0	1009.2
	Pi(mr)	701.9	699.9	698.0	696.4	694.9
	Po(mr)	134.0	157.6	183.8	212.8	244.6
	PT(mr)	835.9	857.5	881.8	909.2	939.5

6. CASE VI-0 [Rotational Velocity II]

For this case the rotational velocity was varied while the tip velocity, solidity and chord were held constant. Table VIII shows the results of these variations.

TABLE VIII

CASE VI-0

Variables	Rot. Vel.	$0.90\Omega_0$	$0.95\Omega_0$	Ω_0	$1.05\Omega_0$	$1.10\Omega_0$
		27.7	29.3	30.8	32.3	33.9
	Radius	26.7	26.3	24.0	22.9	21.8
Power Required	PT(a/c)	905.6	929.1	954.2	980.6	1008.3
	Pi(mr)	625.1	661.5	698.0	734.8	771.6
	Po(mr)	204.2	193.5	183.8	175.0	167.2
	PT(mr)	829.3	855.0	881.8	909.8	938.8

E. PARAMETER VARIATION - CRUISE VELOCITY

A forward velocity of sixty (60) knots was chosen as the cruise velocity for the baseline helicopter.

As the helicopter translates into forward flight it is to be expected that the induced power will cease to be the predominant factor in the composition of the total power. It is also to be expected that the profile power requirements will increase in relation to the square of the forward velocity.

Fuselage drag, which of course contributed nothing to the power requirements at zero velocity, becomes more evident as forward velocity increases. Even though this power component is a function of the cube of the forward velocity, at the speed chosen for cruise in this example, the parasite power will be only approximately ten percent of the total power required for the helicopter.

The baseline component and total power requirements at this velocity are shown in Table IX.

TABLE IX
CRUISE POWER REQUIREMENTS

	MAIN ROTOR	TAIL ROTOR	AIRCRAFT
Induced Power (HP)	238.7	7.9	
Profile Power (HP)	198.7	18.0	
Parasite Power (HP)	56.2		
Total Power (HP)	493.6	25.9	519.5

1. CASE I-60 [Rotor Radius I]

For this case the rotor radius was varied while the rotor chord and tip velocity were held constant. This implies that the solidity was changed (Equation 2-1) as was the rotational velocity (Equation 2-2). Tables X shows the results of these variations.

TABLE X
CASE I-60

Variables	Radius	$0.90R_0$	$0.95R_0$	R_0	$1.05R_0$	$1.10R_0$
		21.6	22.8	24.0	25.2	26.4
	Rot. Vel.	34.2	32.4	30.8	29.3	28.0
Power Required	PT(a/c)	555.7	535.0	519.5	507.3	498.3
	Pi(mr)	295.4	264.9	238.8	216.3	196.9
	Po(mr)	178.8	199.4	198.7	208.5	218.5
	Pp(mr)	56.2	56.2	56.2	56.2	56.2
	PT(mr)	530.4	509.5	493.7	481.0	471.7

2. CASE II-50 [Rotor Radius II]

For this case the rotor radius was varied while the solidity and tip velocity were held constant. This implies that the chord was changed (Equation 2-1) as was the rotational velocity (Equation 2-2). Table XI shows the results of these variations.

TABLE XI
CASE II-60

Variables	Radius	$0.90R_0$	$0.95R_0$	R_0	$1.05R_0$	$1.10R_0$
		21.6	22.8	24.0	25.2	26.4
	Rot. Vel.	34.2	32.4	30.8	29.3	28.0
	Chord	1.76	1.86	1.95	2.06	2.16
Power Required	PT(a/c)	538.1	526.2	519.5	519.4	522.9
	Pi(mr)	295.4	264.9	238.8	216.3	196.9
	Po(mr)	161.6	179.8	198.7	220.3	242.1
	Pp(mr)	56.2	56.2	56.2	56.2	56.2
	PT(mr)	513.2	500.9	493.7	492.8	495.2

3. CASE III-60 [Rotor Radius III]

For this case the rotor radius was varied while the rotor chord and rotational velocity were held constant. This implies that the solidity was changed (Equation 2-1) as was the tip velocity (Equation 2-2) and the disc area. Table XII shows the results of these variations.

TABLE XII
CASE III-60

	Radius	$0.90R_0$	$0.95R_0$	R_0	$1.05R_0$	$1.10R_0$
Variables		21.6	22.8	24.0	25.2	26.4
	Tip Vel.	665.3	702.2	739.2	776.2	813.1
	Area	1465.7	1633.1	1809.6	1995.0	2189.6
	PT(a/c)	511.7	510.5	519.5	538.3	566.8
Power	Pi(mr)	297.2	265.6	238.8	215.9	196.1
Required	Po(mr)	132.6	163.1	198.7	239.8	287.1
	Pp(mr)	56.2	56.2	56.2	56.2	56.2
	PT(mr)	486.0	484.9	493.7	511.9	539.4

4. CASE IV-60 [Rotor Chord]

For this case the rotor chord was varied while the rotor radius and tip velocity were held constant. This implies that only the solidity was changed (Equation 2-1). Table XIII shows the results of these variations.

TABLE XIII
CASE IV-60

Variable	Chord	$0.90c_0$	$0.95c_0$	c_0	$1.05c_0$	$1.10c_0$
		1.76	1.85	1.95	2.05	2.15
	PT(a/c)	499.5	509.0	519.5	530.0	540.6
Power	Pi(mr)	238.8	238.8	238.8	238.8	238.8
Required	Po(mr)	179.3	188.5	198.7	208.9	219.0
	Pp(mr)	56.2	56.2	56.2	56.2	56.2
	PT(mr)	474.3	483.5	493.7	503.9	514.0

5. CASE V-60 [Rotational Velocity I]

For this case the rotational vvelocity was varied while the rotor radius and chord were held constant. This implies that the tip velocity (Equation 2-2) was not a constant. Table XIV shows the results of these variations.

TABLE XIV
CASE V-60

	Rot. Vel.	$0.90\Omega_0$	$0.95\Omega_0$	Ω_0	$1.05\Omega_0$	$1.10\Omega_0$
Variables		27.7	29.3	30.8	32.3	33.9
	Tip Vel.	665.3	702.2	739.2	776.2	813.1
	PT(a/c)	469.5	493.1	519.5	548.8	581.1
Power	Pi(mr)	240.1	239.4	238.8	238.2	237.7
Required	Po(mr)	147.4	171.7	198.7	228.4	261.0
	Pp(mr)	56.2	56.2	56.2	56.2	56.2
	PT(mr)	443.7	476.3	493.7	522.8	554.9

6. CASE VI-60 [Rotational Velocity II]

For this case the rotational velocity was varied while the tip velocity, radius and chord were held constant. Table XV shows the results of these variations.

TABLE XV
CASE VI-60

	Rot. Vel.	$0.90\Omega_0$	$0.95\Omega_0$	Ω_0	$1.05\Omega_0$	$1.10\Omega_0$
Variables		27.7	29.3	30.8	32.3	33.9
	Radius	26.7	26.3	24.0	22.9	21.8
	PT(a/c)	496.7	506.8	519.5	534.5	551.7
Power	Pi(mr)	192.9	215.3	238.8	263.5	289.4
Required	Po(mr)	220.8	209.2	198.7	189.3	180.7
	Pp(mr)	56.2	56.2	56.2	56.2	56.2
	PT(mr)	469.9	480.5	493.7	509.0	526.3

F. PARAMETER VARIATION - MAXIMUM VELOCITY

A maximum forward velocity of one-hundred fifty (150) knots was chosen as the third and last velocity to be considered in this analysis.

At this velocity it is expected that the induced power will be but a small fraction of the total power while the fuselage parasite power will become the dominant factor. It is to be recalled that parasite power is a function of the cube of the forward airspeed, and is therefore quite sensitive to velocity increases.

The power requirements of the baseline helicopter at this velocity are shown in Table XVI.

TABLE XVI
MAXIMUM VELOCITY POWER REQUIREMENTS

	MAIN ROTOR	TAIL ROTOR	AIRCRAFT
Induced Power (HP)	96.2	21.0	
Profile Power (HP)	276.6	24.8	
Parasite Power (HP)	878.3		
Total Power (HP)	1251.1	45.8	1296.9

1. CASE I-150 [Rotor Radius I]

For this case the rotor radius was varied while the rotor chord and tip velocity were held constant. This implies that the solidity was changed (Equation 2-1) as was the rotational velocity (Equation 2-2). Table XVII shows the results of these variations.

TABLE XVII
CASE I-150

Variables	Radius	$0.90R_0$	$0.95R_0$	R_0	$1.05R_0$	$1.10R_0$
		21.6	22.8	24.0	25.2	26.4
	Rot. Vel.	34.2	32.4	30.8	29.3	28.0
Power Required	PT(a/c)	1288.3	1291.2	1296.9	1304.0	1312.5
	Pi(mr)	119.4	106.8	96.2	87.0	79.1
	Po(mr)	248.9	262.4	276.6	290.4	304.3
	Pp(mr)	878.3	878.3	878.3	878.3	878.3
	PT(mr)	1246.6	1247.5	1251.1	1255.7	1261.7

2. CASE II-150 [Rotor Radius II]

For this case the rotor radius was varied while the solidity and tip velocity were held constant. This implies that the chord was changed (Equation 2-1) as was the rotational velocity (Equation 2-2). Table XVIII shows the results of these variations.

TABLE XVIII
CASE II-150

Variables	Radius	$0.90R_0$	$0.95R_0$	R_0	$1.05R_0$	$1.10R_0$
		21.6	22.8	24.0	25.2	26.4
	Rot. Vel.	34.2	32.4	30.8	29.3	28.0
	Chord	1.76	1.86	1.95	2.06	2.16
Power Required	PT(a/c)	1263.8	1278.9	1296.9	1320.9	1346.7
	Pi(mr)	119.4	106.8	96.2	87.0	79.1
	Po(mr)	225.1	250.4	276.6	306.8	337.1
	Pp(mr)	878.3	878.3	878.3	878.3	878.3
	PT(mr)	1222.8	1235.5	1251.1	1272.1	1294.5

3. CASE III-150 [Rotor Radius III]

For this case the rotor radius was varied while the rotor chord and rotational velocity were held constant. This implies that the solidity was changed (Equation 2-1) as was the tip velocity (Equation 2-2) and the disc area. Table XIX shows the results of these variations.

TABLE XIX
CASE III-150

Variables	Radius	$0.90R_0$ 21.6	$0.95R_0$ 22.8	R_0 24.0	$1.05R_0$ 25.2	$1.05R_0$ 26.4
	Tip Vel.	665.3	702.2	739.2	776.2	813.1
	Area	1465.7	1633.1	1809.6	1955.0	2189.6
Power Required	PT(a/c)	1238.2	1263.7	1297.0	1338.1	1387.5
	Pi(mr)	120.1	107.1	96.2	86.8	78.8
	Po(mr)	195.8	233.5	276.6	325.8	381.4
	Pp(mr)	878.3	878.3	878.3	878.3	878.3
	PT(mr)	1194.2	1218.9	1251.1	1290.9	1338.5

4. CASE IV-150 [Rotor Chord]

For this case the rotor chord was varied while the rotor radius and tip velocity were held constant. This implies that only the solidity was changed (Equation 2-1). Table XX shows the results of these variations.

TABLE XX
CASE IV-150

Variable	Chord	$0.90c_0$ 1.76	$0.95c_0$ 1.85	c_0 1.95	$1.05c_0$ 2.05	$1.10c_0$ 2.15
Power Required	PT(a/c)	1269.1	1282.3	1296.9	1311.6	1326.3
	Pi(mr)	96.2	96.2	96.2	96.2	96.2
	Po(mr)	249.7	262.5	276.6	290.8	305.0
	Pp(mr)	878.3	878.3	878.3	878.3	878.3
	PT(mr)	1224.2	1237.0	1251.1	1265.3	1279.5

5. CASE V-150 [Rotational Velocity I]

For this case the rotational velocity was varied while the rotor radius and chord were held constant. This implies that the tip velocity (Equation 2-2) was not a constant. Table XXI shows the results of these variations.

TABLE XXI
CASE V-150

	Rot. Vel.	$0.90\Omega_0$	$0.95\Omega_0$	Ω_0	$1.05\Omega_0$	$1.10\Omega_0$
Variables		27.7	29.3	30.8	32.3	33.9
	Tip Vel.	665.3	702.2	739.2	776.2	813.1
	PT(a/c)	1241.0	1267.5	1296.9	1329.4	1364.9
Power	Pi(mr)	96.7	96.4	96.2	95.9	95.7
Required	Po(mr)	217.5	245.8	276 6	310.3	346.8
	Pp(mr)	878.3	878.3	878.3	878.3	878.3
	PT(mr)	1192.5	1220.5	1251.1	1284.5	1320.85

6. CASE VI-150 [Rotational Velocity II]

For this case the rotational velocity was varied while the tip velocity, radius and chord were held constant. Table XXII shows the results of these variations.

TABLE XXII
CASE VI-150

	Rot. Vel.	$0.90\Omega_0$	$0.95\Omega_0$	Ω_0	$1.05\Omega_0$	$1.10\Omega_0$
Variables		27.7	29.3	30.8	32.3	33.9
	Radius	26.7	25.3	24.0	22.9	21.8
	PT(a/c)	1314.7	1304.3	1296.9	1291.9	1288.8
Power	Pi(mr)	77.5	86.6	96.2	106.2	116.9
Required	Po(mr)	307.5	291.1	276.6	263.6	251.6
	Pp(mr)	878.3	878.3	878.3	878.3	878.3
	PT(mr)	1263.3	1256.0	1251.1	1248.1	1246.8

IV. ANALYSIS

A. INTRODUCTION

The geometric parameters that were varied in this investigation were all related to the main rotor, and therefore directly affected the main rotor power. But, inasmuch as the tail rotor power is a function of the main rotor torque, and therefore the main rotor power, analysis will be made as to the effect of the parameter change on the total power required.

Because the total power varies with forward flight, the findings were non-dimensionalized by referring the percent change in the parameter to the percent change in total power required. The figures of this chapter show these relationships separately for each of the six cases for each of the three velocities, as well as composite summary presentations. For each case, comments will be made as to the overall effect of the parameter change on the total power required, as well as an analysis of the primary contribution to the change. The induced power (Pi) and the profile power (Po) trends are shown with up or down arrows at the extremes of the basic parameter change scale.

B. HOVER

Figures 4.1 - 4.6 show the changes in power required for each of the six -0 cases presented in Chapter III.

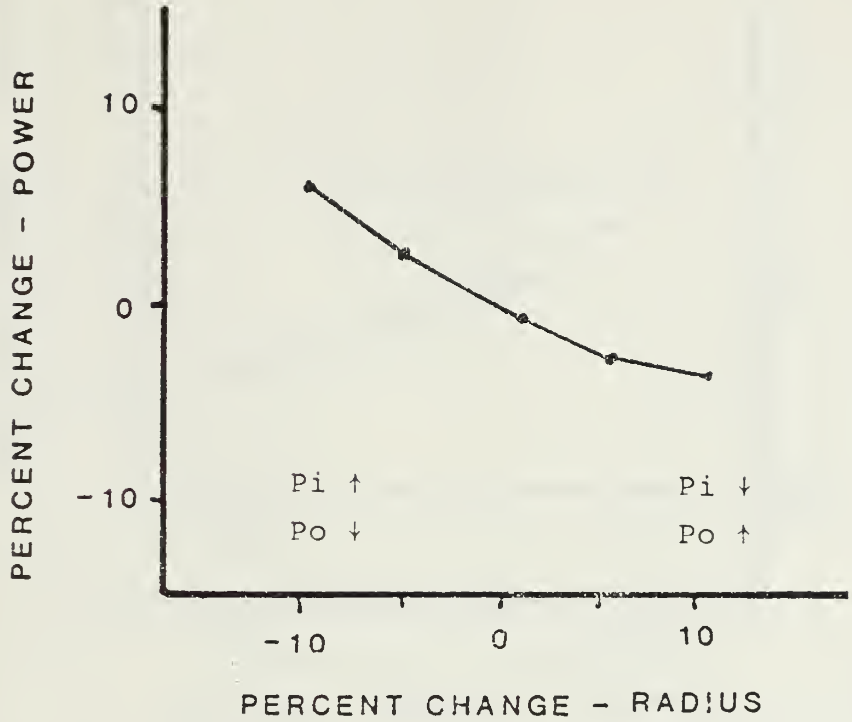

Figure 4.1 - Case I-0

1. CASE I-0 [Rotor Radius I]

For this case it is to be seen that the total power decreases as the rotor radius is increased. At the low end of the radius scale (0.90R) the main rotor induced power has been increased from the base value while the main rotor profile power has been decreased. At the high end of the radius scale (1.10R) the reverse effect is observed. This indicates that the change in induced power is the dominant effect for this change.

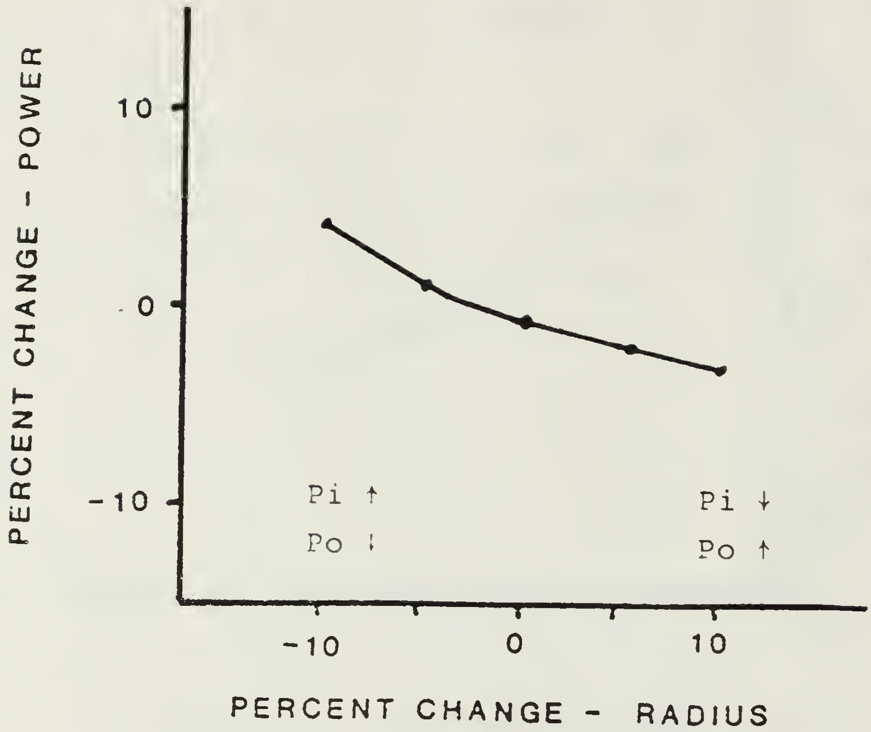

Figure 4.2 - Case II-0

2. <u>CASE II-0 [Rotor Radius II]</u>

Once again it is seen that the total power required decreases as the main rotor radius increases. As with the previous case, the induced power increases as radius is reduced and decreases as radius is increased, with the profile power change moving in the opposite direction.

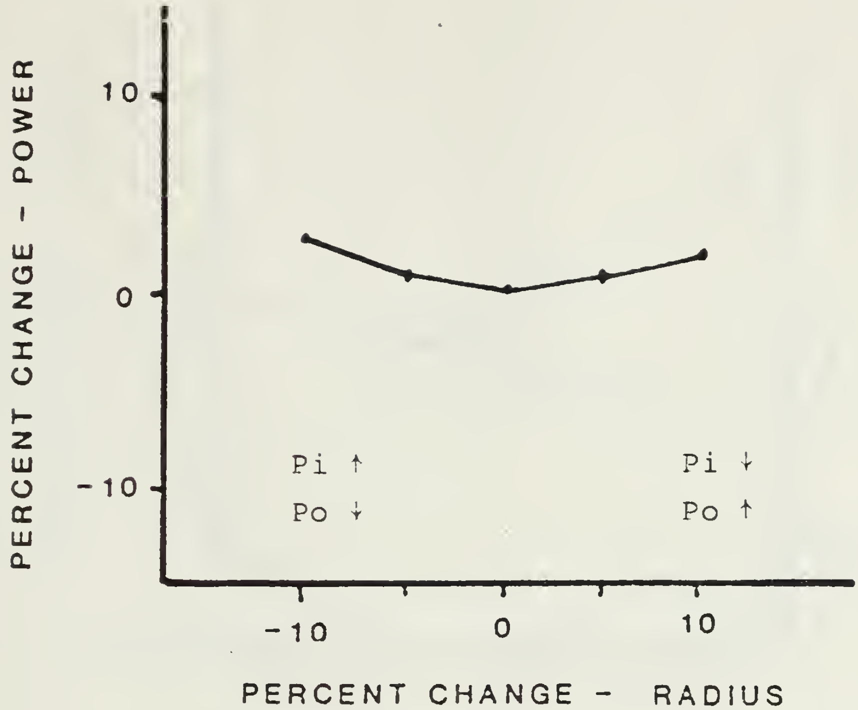

Figure 4.3 - Case III-0

3. <u>CASE III-0 [Rotor Radius III]</u>

For this case it is seen that the power increases with both a decrease in rotor radius or an increase in radius. Once again, the induced power required increases with a decrease in radius and decreases as the radius is increased with the profile power reacting in the opposite manner.

Inasmuch as this case represents the most elementary change involving the radius, that is to say simply changing the radius without altering the rotational velocity or the chord, it appears that an optimum radius could be chosen for hover flight, once other factors are selected.

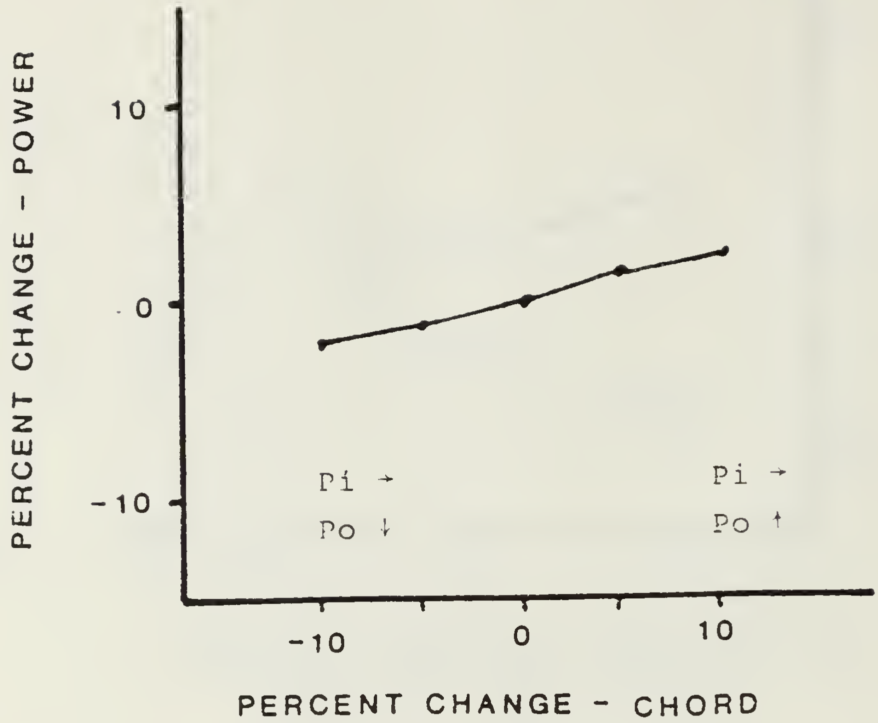

Figure 4.4 - Case IV-0

4. Case IV-0 [Rotor Chord]

This figure indicates that as the chord is increased, the total power required also increases. Because the induced power determinations were made using Momentum Theory, blade chord does not appear as a factor in the induced power. This explains the lack of change of this power component with chord changes.

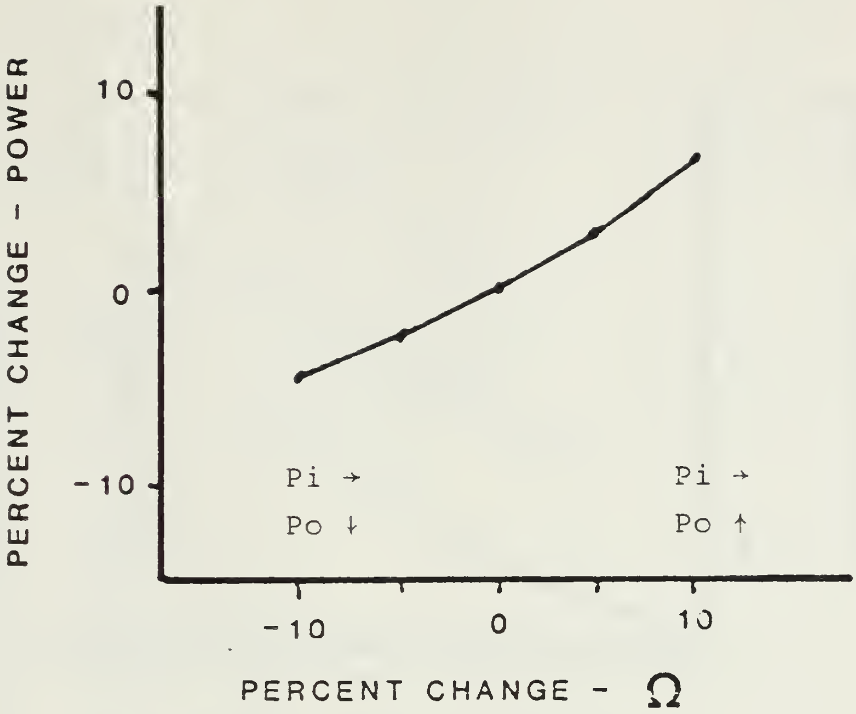

Figure 4.5 - Case V-0

5. <u>CASE V-0 [Rotational Velocity I]</u>

An increase in rotational velocity results in an increase in total power required, as shown in Figure 4.5. However, it is necessary that the rotational velocity be sufficient to provide for the generation of the required thrust. If the rotational velocity is too low, a large angle of attack of the blades will be required. This will not only result in an increase in induced power, but will also produce an increase in profile drag coefficient, which will increase the profile power required.

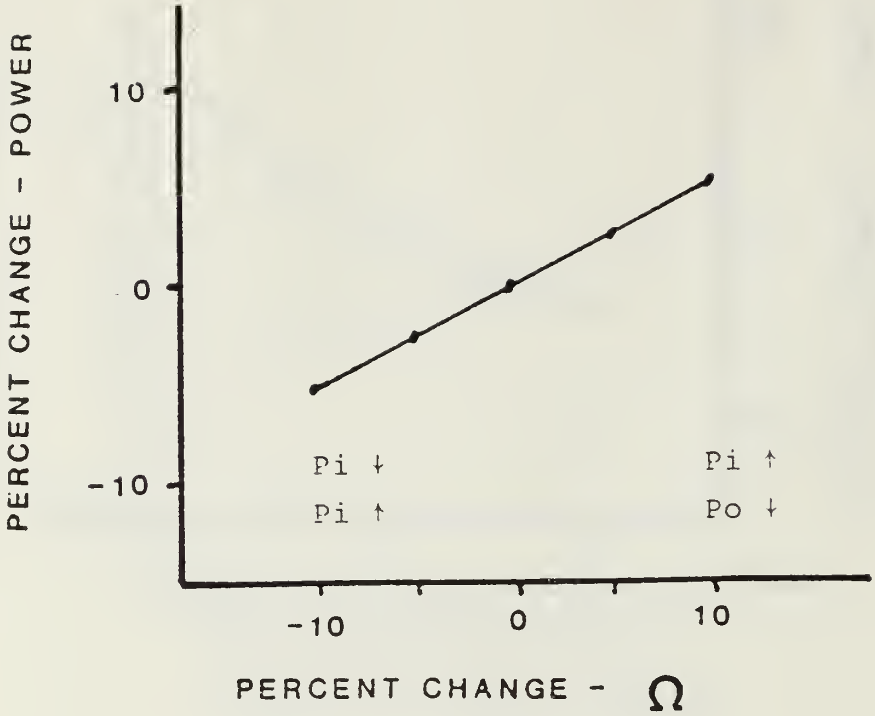

Figure 4.6 - Case VI-0

6. CASE VI-0 [Rotational Velocity II]

The overall effects of a change in rotational velocity in this case are somewhat similar to those of the previous case, but there are differences here in the causes of the change. Because this case involves not only a change in rotational velocity but also a change in rotor radius (to maintain a constant tip velocity), the induced power is changed as is the profile power. In fact, it is seen that the change in the induced power is the dominant factor.

C. CRUISE VELOCITY

Figures 4.7 - 4.12 show the changes in total power required for each of the six -60 cases.

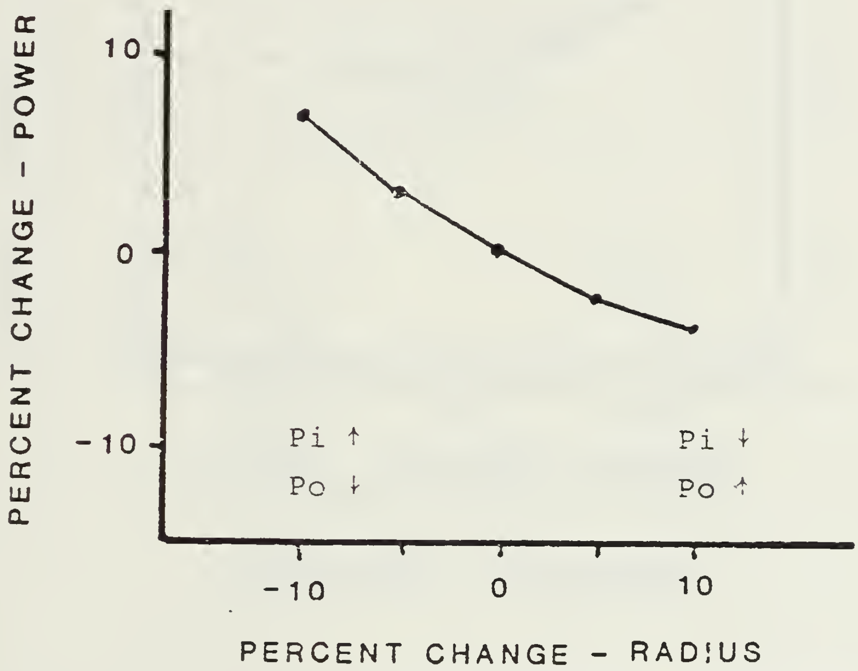

Figure 4.7 - Case I-60

1. <u>CASE I-60 [Rotor Radius I]</u>

An increase in rotor radius results in a decrease in total power required. In this set of cases, although the induced power has been reduced from the hover case, the forward velocity is still low enough to provide for the induced power effects. It is seen that the induced power is the dominant factor in this case.

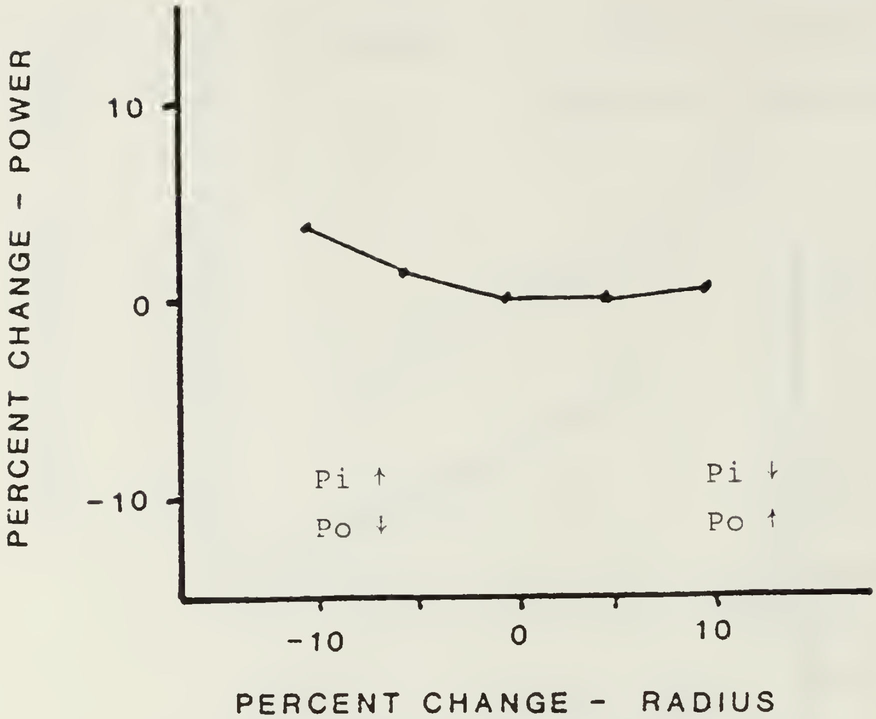

Figure 4.8 - Case II-60

2. <u>CASE II-60 [Rotor Radius II]</u>

Once again the induced power causes an increase in total power at low values of radius, but the effect of the induced power is partially overcome at the larger radius values by the profile power term.

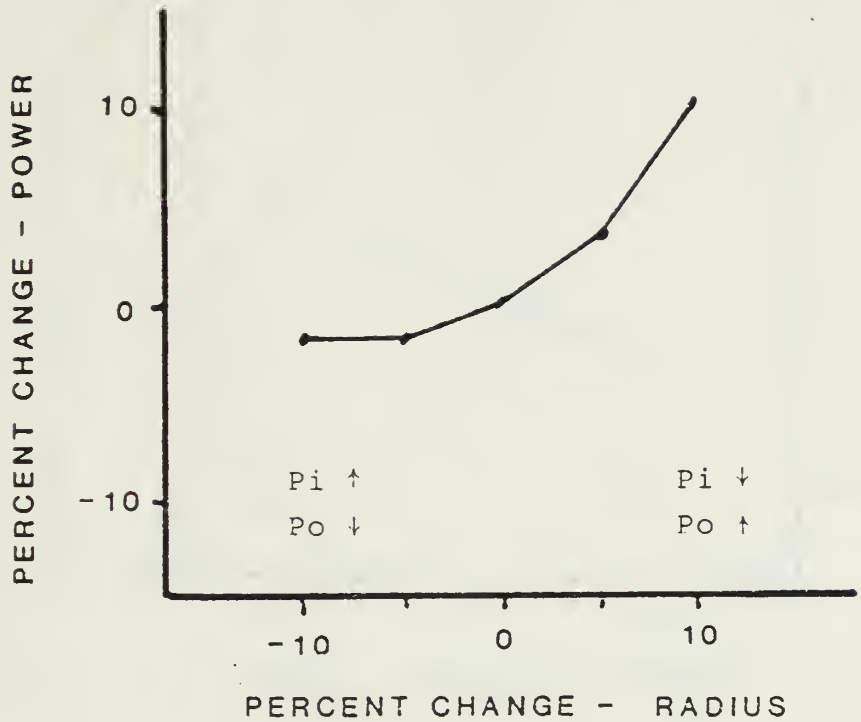

Figure 4.9 - Case III-60

3. <u>CASE III-60 [Rotor Radius III]</u>

The increase in tip velocity as the rotor radius is changed with a constant rotational velocity in this case results in a rapid increase in total power required as the radius is increased. The dominant factor is the increase in profile power requirements.

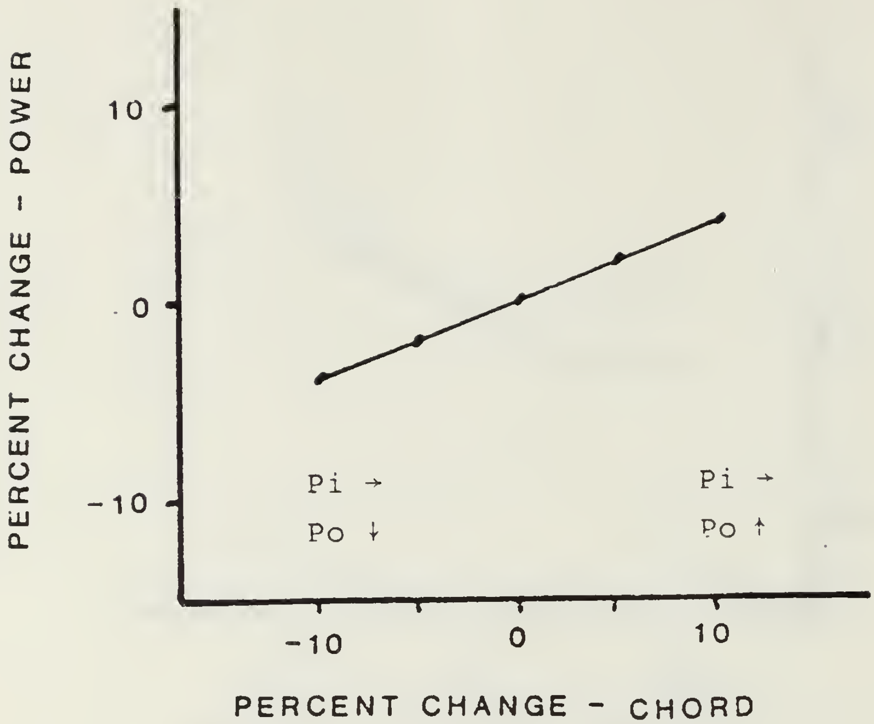

Figure 4.10 - Case IV-60

4. <u>CASE IV-60 [Rotor Chord]</u>

As in the hover case, increasing the chord produces an increase in total power required. The effect at cruise velocity is even more pronounced because of the general increase in profile power at velocity over that at hover. Profile power is the dominant factor.

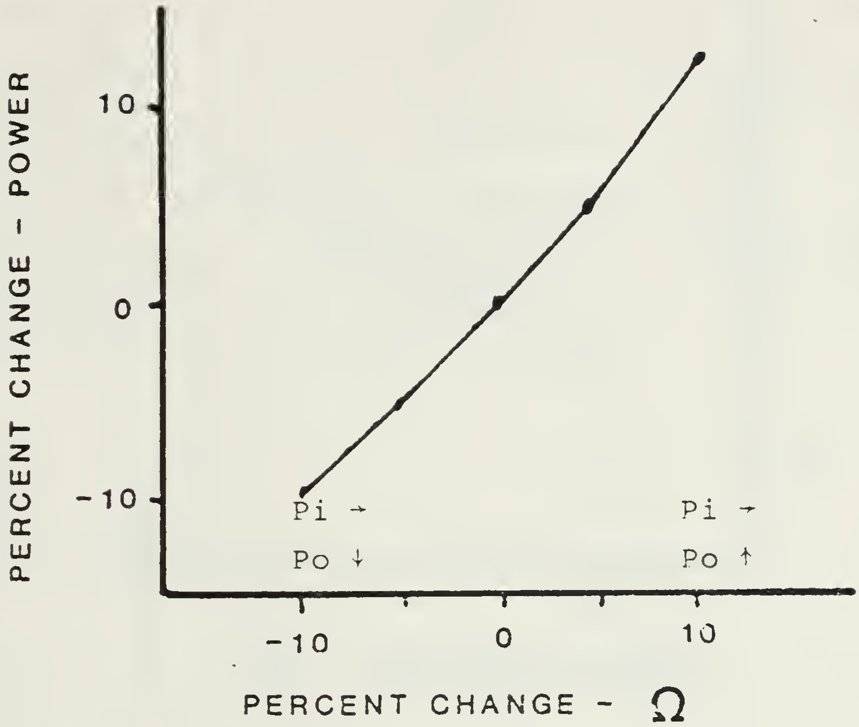

Figure 4.11 - Case V-60

5. <u>CASE V-60 [Rotational Velocity I]</u>

The cubic term for tip velocity in the profile power equation results in a substantial increase in total power required as the rotational velocity is increased. Again, one must recall that although there is no apparent effect on induced power, the required angle of attack and the developed lift of the blades are very sensitive to the rotational velocity. Profile power is the dominant factor.

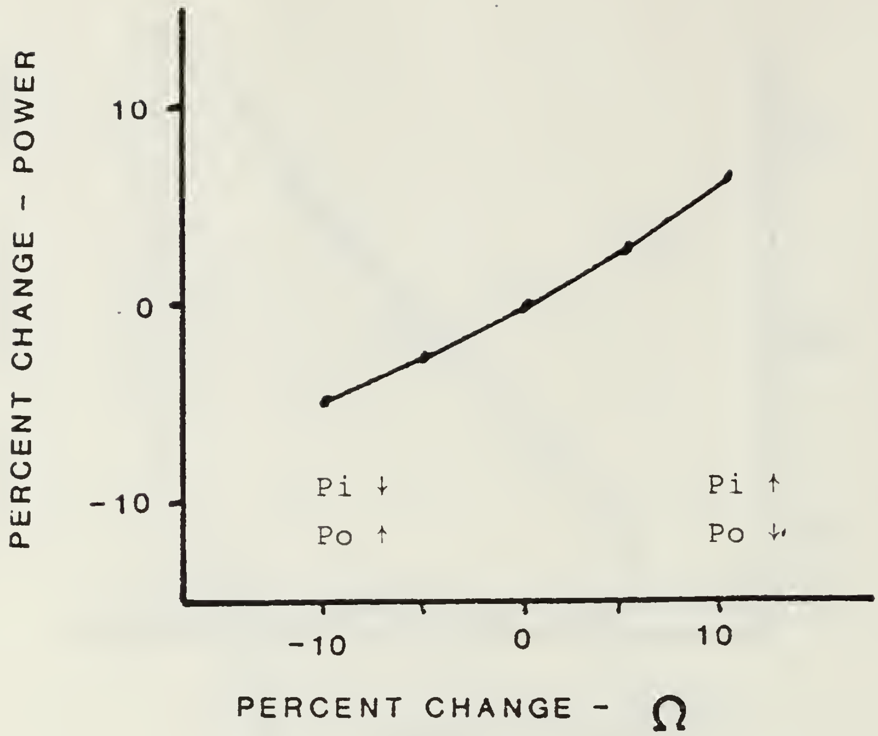

Figure 4.12 - Case V1-60

6. <u>CASE VI-60 [Rotational Velocity II]</u>

Here with a rotational velocity increase, the rotor radius is decreased so as to maintain a constant tip velocity. Although the total power increases as in Case V-60 in Figure 4.11, the cause here is principally the change in induced power that results from the radius change. It is to be noted for this case that the profile power trend is opposite from that of Case V-60.

D. MAXIMUM VELOCITY

At the higher velocities, the effects of induced power become minimum and the total power is dominated by the profile and parasite power terms. Inasmuch as none of the parameters which have been varied affect the parasite power, it is expected that profile power rerquirements will dominate in the cases shown in Figures 4.13 - 4.18.

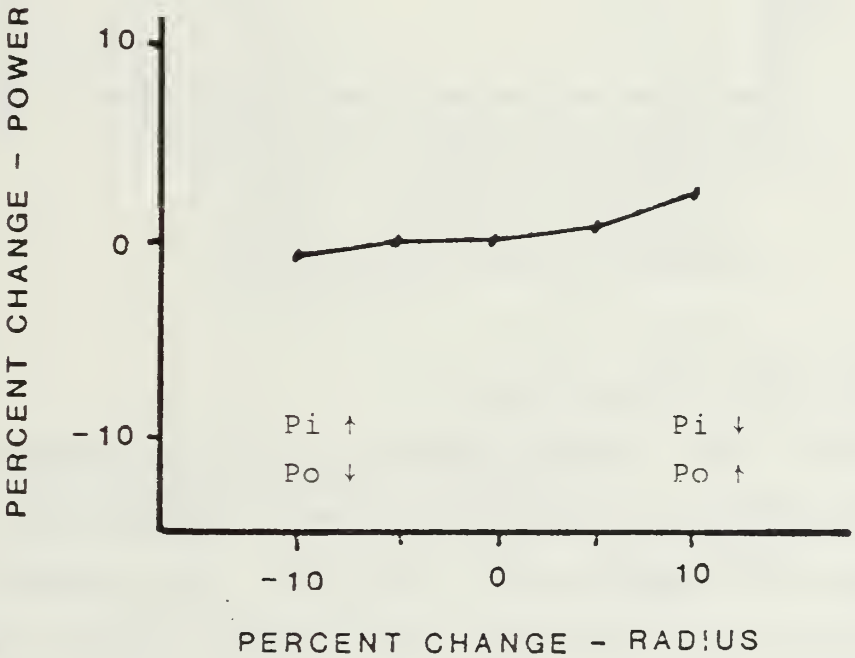

Figure 4.13 - Case I-150

1. CASE I-150 [Rotor Radius I]

Only a slight change is observed with changes in rotor radius in this case. The opposite effects of induced and profile power nearly cancel each other.

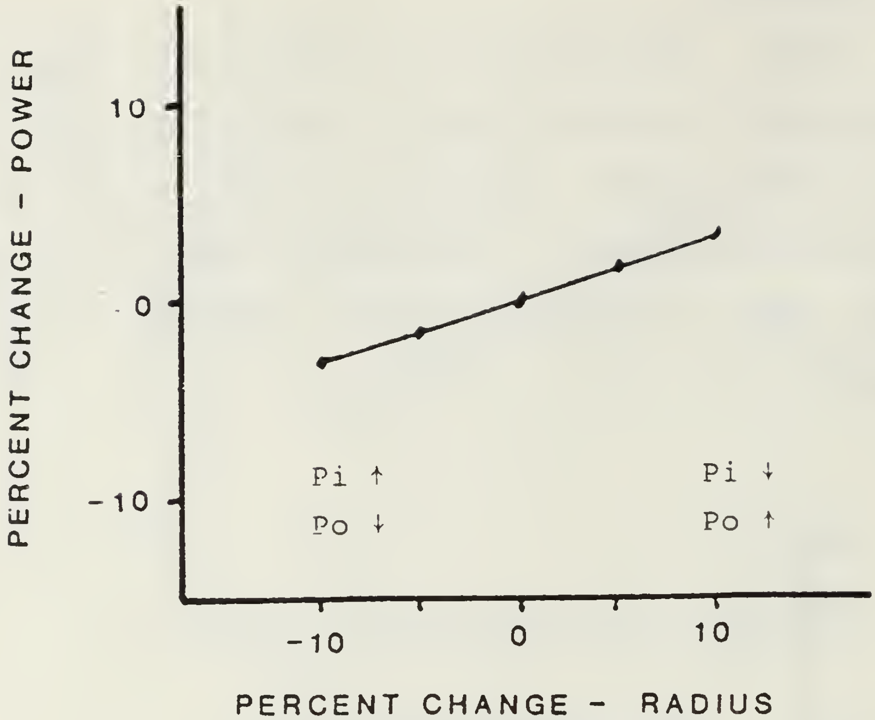

Figure 4.14 - Case II-150

2. CASE II-150 [Rotor Radius II]

A small, but steady increase in total power is observed as the rotor radius is increased in this case. Inasmuch as the overall trend is opposite to that of the induced power requirements, it is seen that the profile power needs are predominant.

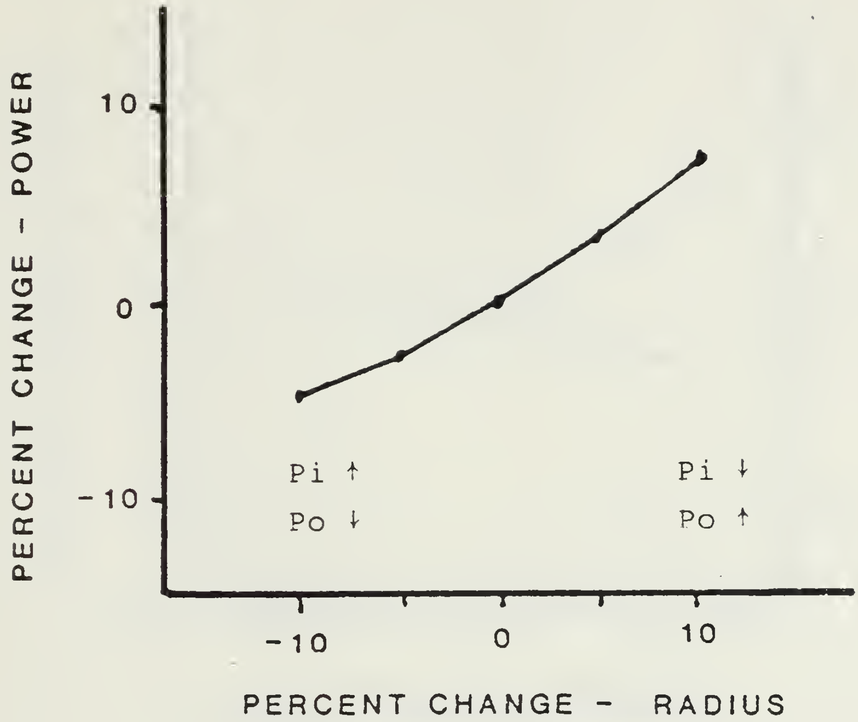

Figure 4.15 - Case III-150

3. <u>CASE III-150 [Rotor Radius III]</u>

Increasing the rotor radius while maintaining a constant rotational velocity results in an increased tip velocity. The effect of this change on profile power and on the total power is evident from Figure 4.15. The profile power is dominant.

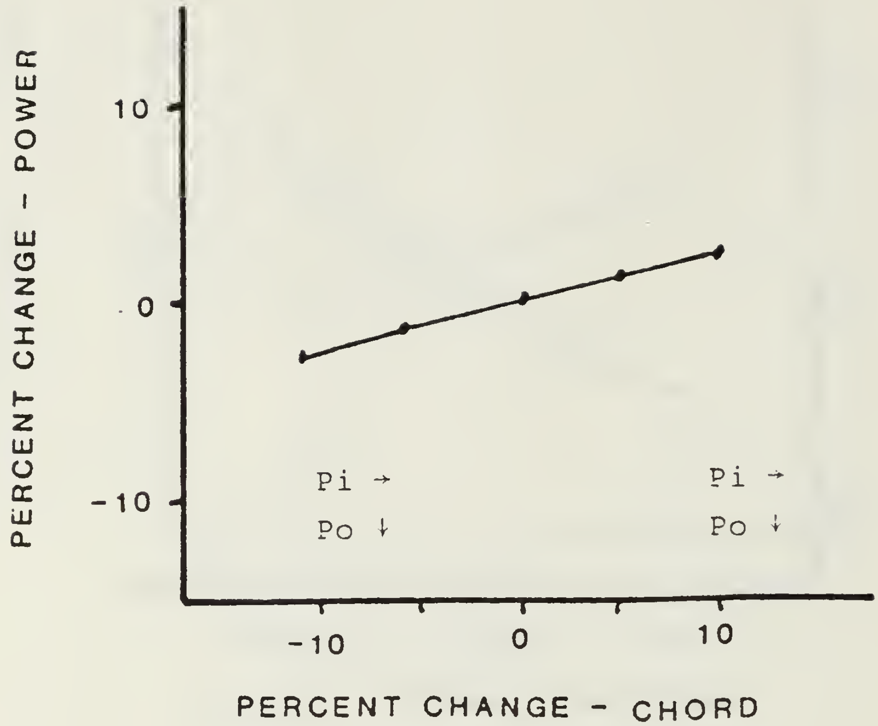

Figure 4.16 - Case IV-150

4. <u>CASE IV-150 [Rotor Chord]</u>

Increasing the chord has a steadily increasing effect on the total power. However, it is to be observed that a ten percent (10%) change in chord dimension results in only approximately a three percent (3%) change in total power at this velocity. Profile power is dominant.

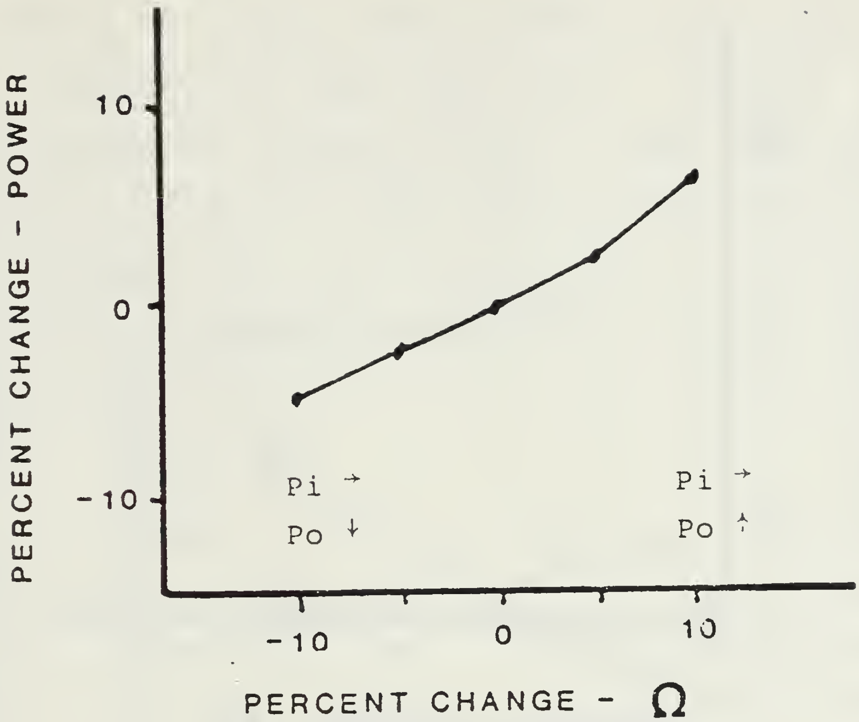

Figure 4.17 - CAse V-150

5. <u>CASE V-150 [Rotational Velocity I]</u>

Increasing the rotational velocity while holding the rotor radius constant results in an increase in the tip velocity and a rise in the total power required. The profile power is the dominant factor.

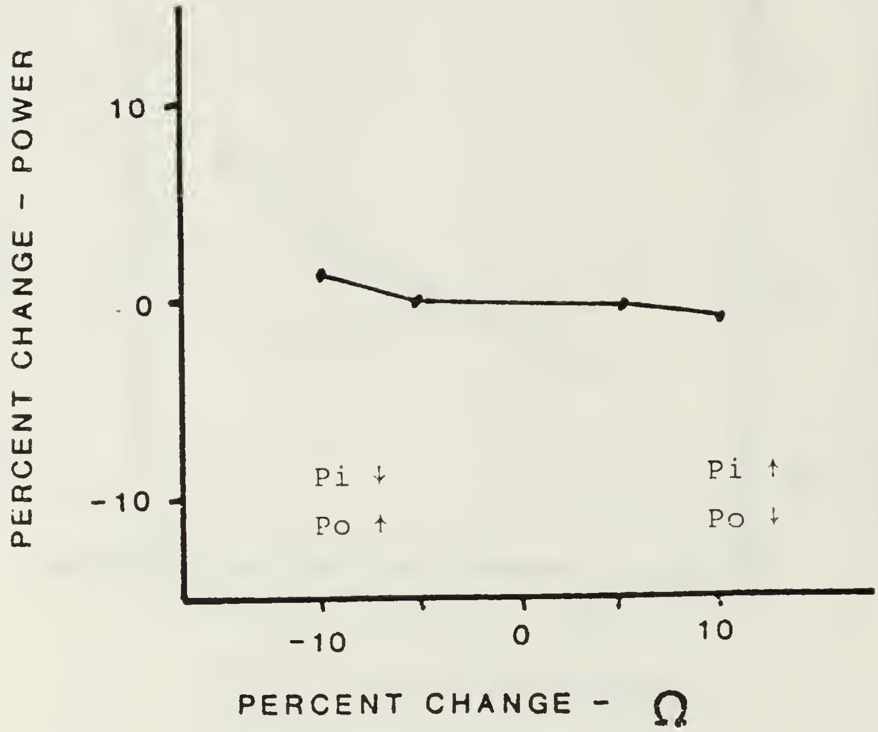

Figure 4.18 - Case VI-150

6. <u>CASE VI-150 [Rotational Velocity II]</u>

When the rotational velocity and the rotor radius are changed at the same time so as to maintain a constant tip velocity, there is negligible effect on the total power requirements. The compensating effects from the induced and profile power components indicate that there is no dominant factor.

E. SUMMARY

In order to observe more closely the effects of these parameter variations over the entire velocity range, the composite percentage changes in total power have been plotted in Figures 4.19 - 4.24 for each of the six cases for the three velocity values.

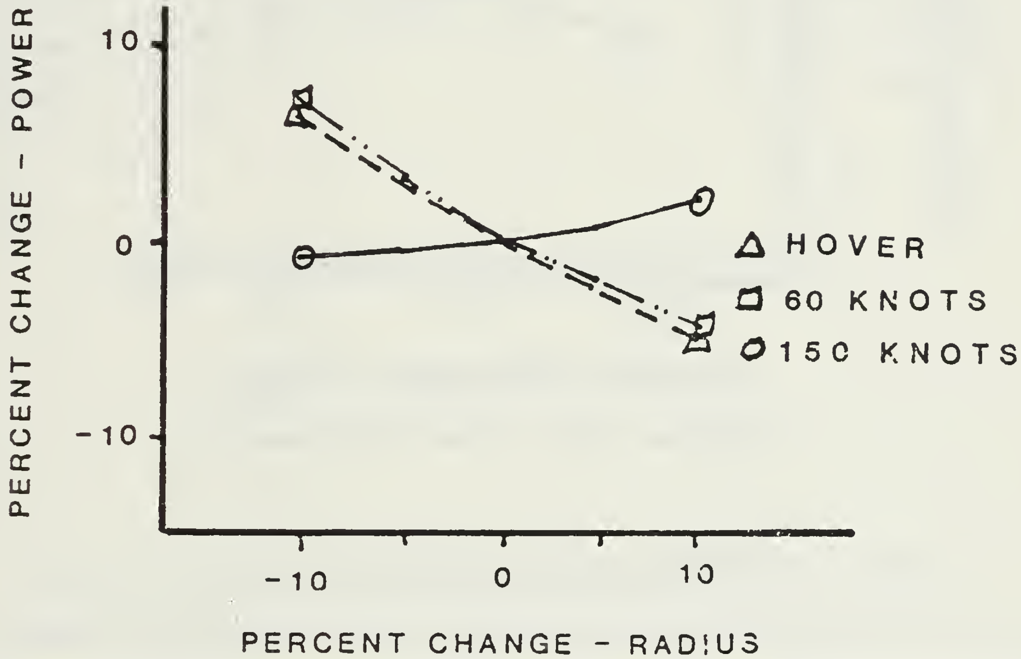

Figure 4.19 - Case I-Summary

1. CASE I-SUMMARY [Rotor Radius I]

It is seen that the improvement in total power with an increase in rotor radius that is evident at the lower velocities is reversed at high speed. This gives the designer cause to ponder as to at what velocity the helicopter should be optimized.

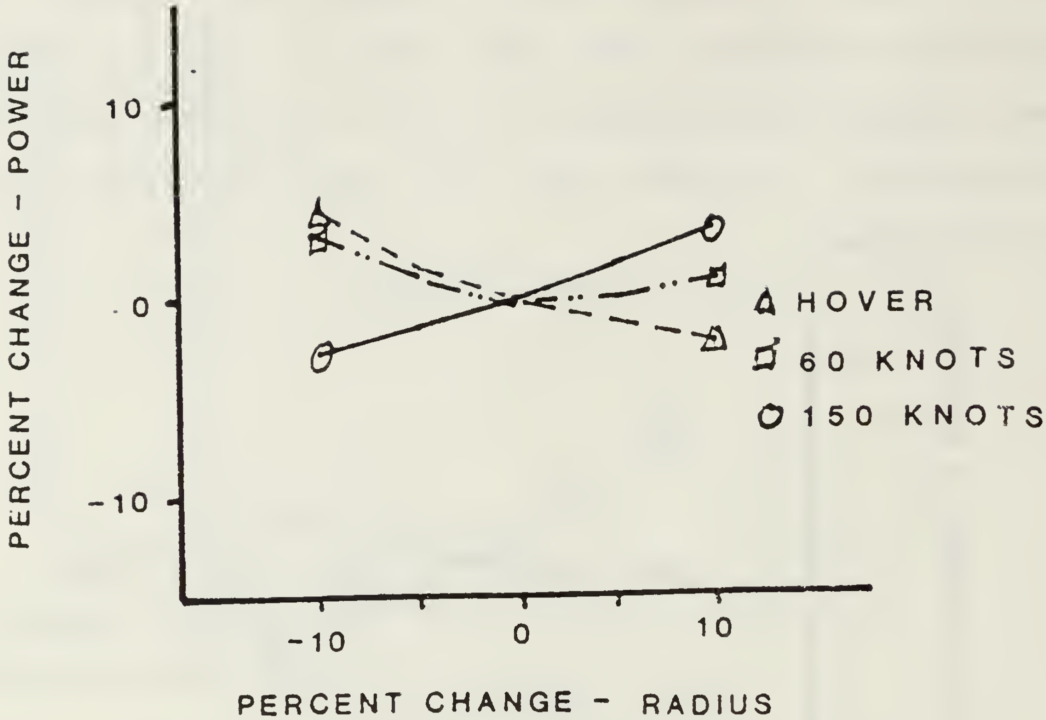

Figure 4.20 - Case II-Summary

2. <u>CASE II-SUMMARY [Rotor Radius II]</u>

Again the high forward velocity region results in a reversal of the total power trend, but it is to be observed that an increase in radius produces an increase in total power even at the cruise speed.

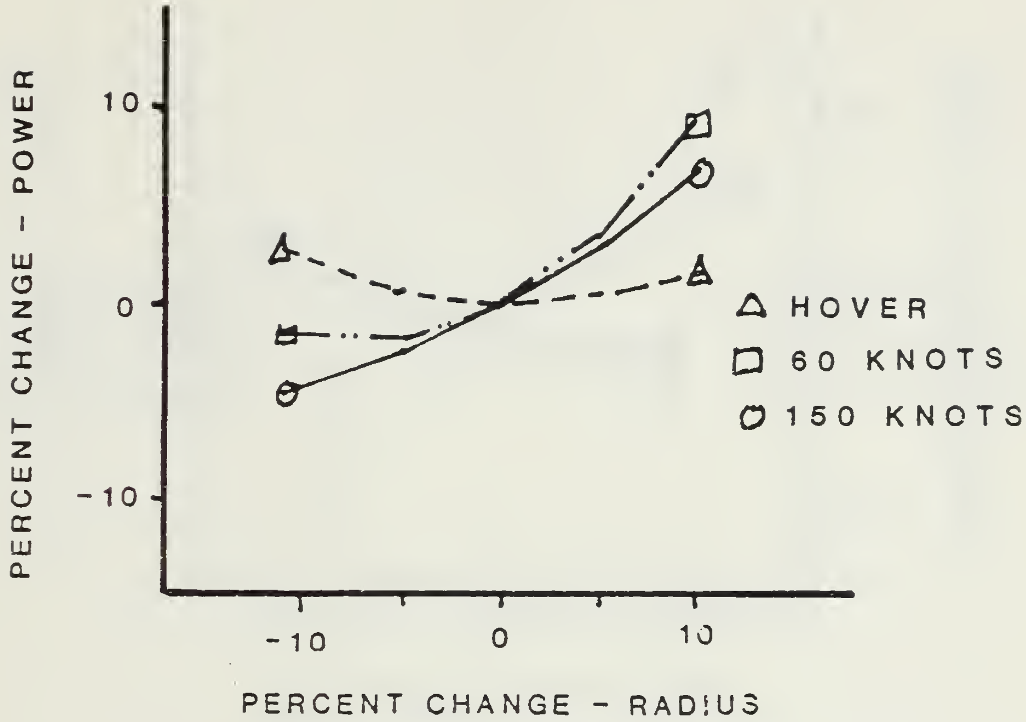

Figure 4.21 - CAse III - Summary

3. <u>CASE III-SUMMARY [Rotor Radius III]</u>

Only at hover is there a minimum point in the power required in this case. Once again, the designer must consider carefully at what velocity the performance should be optimized.

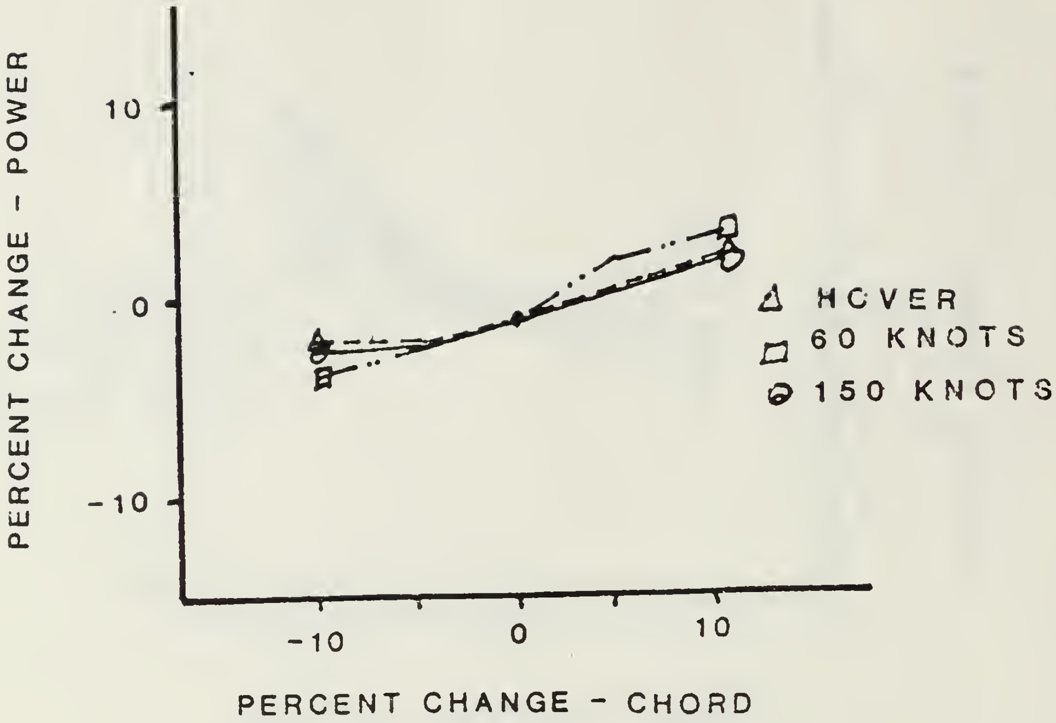

Figure 4.22 - Case IV-Summary

4. <u>CASE IV-SUMMARY [Rotor Chord]</u>

Although this summary plot indicates an increasing power requirements at all velocities, it should be noted that the percentage change in total power is really very small.

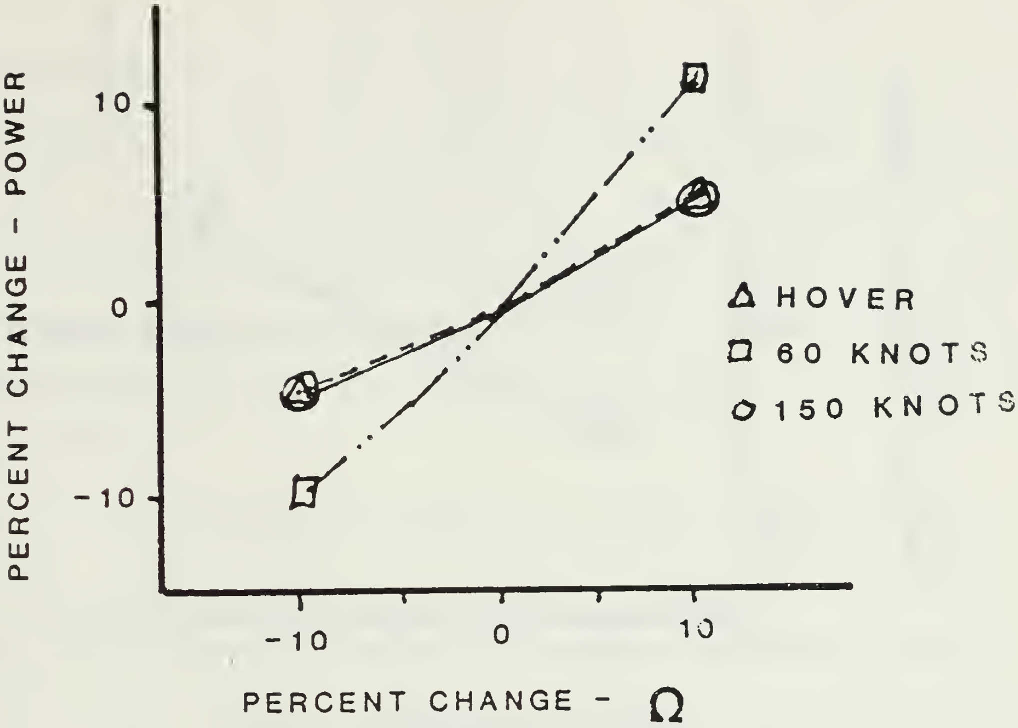

Figure 4.23 - Case V-Summary

5. CASE V-SUMMARY [Rotational Velocity I]

In Figure 4.23 it is seen that increasing the rotational velocity while holding the rotor radius constant produces an increase in total power required at all velocities, with a more drastic increase at the mid-velocity (60 knots) region.

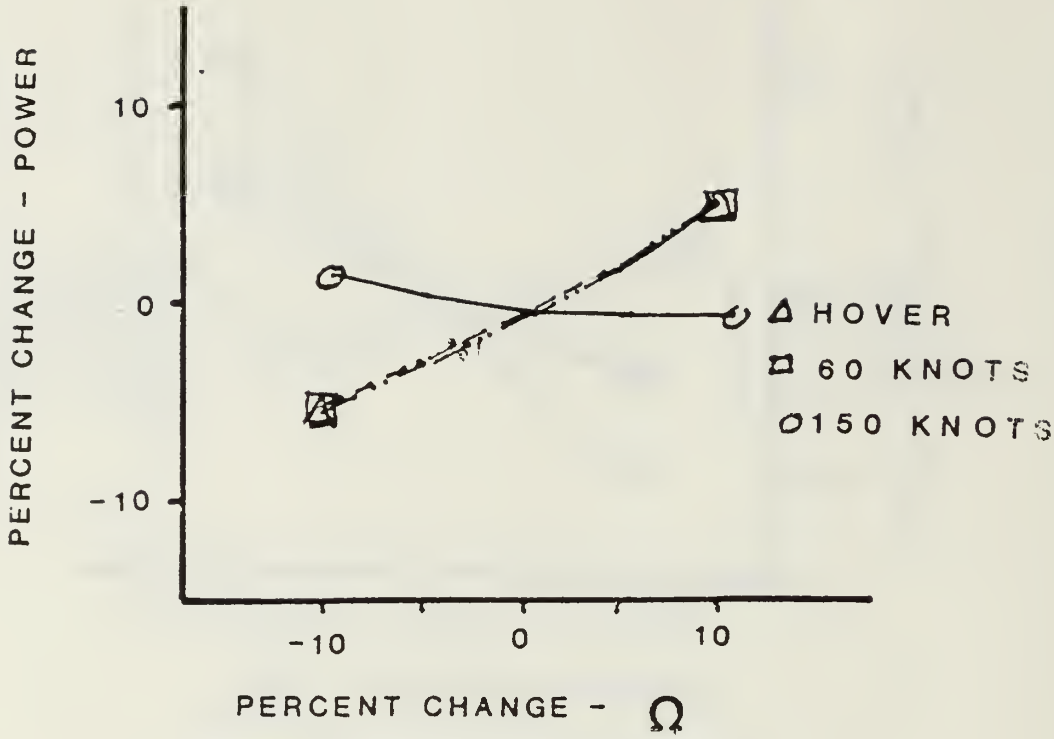

Figure 4.24 - Case VI-Summary

6. CASE VI-SUMMARY [Rotational Velocity II]

Increasing the rotational velocity while decreasing the rotor radius so as to maintain a constant tip velocity results in an increase in total power required at the lower velocities and produces a very slight decrease in power requirements at maximum velocity.

V . CONCLUSIONS AND RECOMMENDATIONS

A. CONCLUSIONS

This project allows the user to examine some general trends that could be used in the early stages of a helicopter design. It should be restated that the trends developed in this project are only for the baseline helicopter and may be different for heavier or lighter vehicles.

From the analysis of Chapter IV it is seen that if the radius is changed the total power requirements differ according to both how the other geometric parameters change and the velocity of the helicopter. This means that the designer must perform a sensitivity analysis for each of the possible options that are to be considered.

If there can be any general conclusions drawn from this study it is that an increase of rotor chord generally produces an increase in total power required at all velocities as does an increase in rotational velocity.

B. RECOMMENDATIONS

In order to broaden the information presented herein, it is recommended that a similar task be undertaken for at least three other helicopter weights - less than 5,000 pounds, 20,000 pounds and greater than 50,000 pounds.

The results of these studies could then be compared with this project in an effort to learn if the trends noted in this study are typical across the helicopter weight range.

LIST OF REFERENCES

1. Layton, Donald M., Helicopter Design Manual, Naval Postgraduate School, Monterey, California 1984.

2. Layton, Donald M., Helicopter Performance, Matrix Publishers, Inc. Beaverton, OR, 1984

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